PERGAMON

Renewable and Sustainable Energy Reviews
5 (2001) 59–77

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Evaluation of solar energy research and its applications in Saudi Arabia — 20 years of experience

Saleh H. Alawaji *

Energy Research Institute (ERI), King Abdulaziz City for Science And Technology (KACST), Riyadh, Saudi Arabia

Received 6 June 2000; accepted 13 June 2000

Abstract

Since the mid-seventies Saudi Arabia has been at the forefront of research and development into solar energy. For example, two major international joint research and development (R&D) programs were funded, in cooperation with the United States of America and the Federal Republic of Germany, aimed at developing renewable energy technology and demonstrating its applications by designing and installing several pilot projects. After more than 20 years of research and development it now becomes essential to evaluate these R&D activities in order to determine their benefits to the scientific community, the country, and society in general. This paper therefore presents an evaluation of a number of research projects in terms of their technical and economical performance and feasibility. The paper also discusses the various lessons that have been learned through the operation and maintenance of these projects, and considers the various reasons underlying either their success or failure. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

With one-fourth of the world's proven oil reserves, Saudi Arabia is likely to remain the world's largest oil producer for the foreseeable future. Saudi Arabia's proven gas reserves are estimated at 204.5 trillion cubic feet (tcf), ranking fifth in the world

* Tel.: +966-1481-3500; fax: +966-1481-3880.
E-mail address: sawaji@kacst.edu.sa (S.H. Alawaji).

PII: S1364-0321(00)00006-X

(after Russia, Iran, Qatar, and the United Arab Emirates (UAE)). Saudi Arabia is a relatively rich and rapidly developing country and so demand for electricity is growing on average at around 5% annually. Over the next 25 years, it is estimated that US$117 billion will be invested in the country's power sector, with most of this to be raised by the private sector, in order to expand capacity and build a national power grid. It is estimated that 2000 megawatts (MW) of new capacity will be installed each year up until 2020 [1]. Saudi Arabia also has moved slowly towards cuts in government subsidies to the electricity sector and has revised its electricity tariff rates. Recently, a new electricity tariff has also been approved.

Recognizing the sun as a major natural resource — with which Saudi Arabia is blessed in abundant measure (2200 thermal kilowatt hours (kWh) per square meter) — it is believed that solar energy is a valuable and renewable energy source that should be fully exploited for the benefit of the country. Even though Saudi Arabia is a leading oil producer, it is keenly interested in taking an active part in the development of new technologies for exploiting and utilizing renewable sources of energy because of the following considerations:

(i) Saudi Arabia has an area of more than 2 million km^2 where many remote villages and settlements can benefit from renewable energy applications.

(ii) Saudi Arabia has enormous potential for exploiting solar energy. Therefore, if a major breakthrough is achieved in the field of solar-energy conversion, Saudi Arabia can be a leading producer and exporter of solar energy in the form of electricity.

(iii) Renewable energy sources are essentially considered as providing supportive to depletable sources of energy (hydrocarbon resources), which in the past were generously consumed and dissipated. It is the Kingdom's view that such exhaustible resources ought to be used more wisely, for the development of other products more beneficial and useful to humankind, such as petro-chemicals.

Applications of solar energy in Saudi Arabia have been growing since 1960. Research activities commenced with small-scale university projects during 1969, and systematized major R&D work for the development of solar energy technologies was started by the King Abdulaziz City for Science and Technology (KACST) in 1977. For the last two decades the Energy Research Institute (ERI) at KACST has conducted major research, development and demonstration (RD&D) work in this field. The ERI has a number of international joint programs in the field of solar energy including SOLERAS with the United States of America, and HYSOLAR with the Federal Republic of Germany. These joint programs were directed towards projects that were of mutual interest to the committed countries involved and concentrated on large demonstration projects such as electricity generation, water desalination, agricultural applications, and cooling systems.

The main purpose of this paper is to review and evaluate those R&D projects on solar energy executed and maintained by the ERI during the last two decades. The

paper also discusses the various lessons learned through operation and maintenance of selected projects, and explores the different reasons underlying either their success or failure. Major solar energy RD&D projects executed by the ERI are listed in Table 1. A brief description of the selected projects and their associated technical accomplishments will follow.

Table 1
List of solar energy projects conducted by the ERI, KACST

Projects	Location	Duration	Applications
350 kW PV system (2155 MWh)	Solar Village	1981–87	AC/DC electricity for remote areas
350 kW PV hydrogen production plant (1.6 MWh)	Solar Village	1987–93	Demonstration plant for solar hydrogen production
Solar cooling	Saudi universities	1981–87	Developing of solar cooling laboratory
1 kW solar hydrogen generator (20–30 kWh)	Solar Village	1989–93	Hydrogen production, testing and measurement (laboratory scale)
2 kW solar hydrogen (50 kWh)	KAU, Jeddah	1986–91	Testing of different electrode materials for solar hydrogen plant
3 kW PV test system	Solar Village	1987–90	Demonstration of climatic effects
4 kW PV system	Southern regions of Saudi Arabia	1996	AC/DC electricity for remote areas
6 kW PV system	Solar Village	1996–98	PV grid connection
Solar seawater desalination			
PV water desalination (0.6 m^3 per hour)	Sadous Village	1994–99	PV/RO interface
Solar-thermal desalination	Solar Village	1996-97	Solar distillation of brackish water
PV in agriculture (4 kWp)	Muzahmia	1996	AC/DC grid connected
Long-term performance of PV (3 kW)	Solar Village	Since 1990	Performance evaluation
Fuel cell development (100–1000 W)	Solar Village	1993-2000	Hydrogen utilization
Internal combustion engine (ICE)	Solar Village	1993–95	Hydrogen utilization
Solar radiation measurement	12 stations	1994–2000	Saudi solar atlas
Wind energy measurement	5 stations	1994–2000	Saudi solar atlas
Solar dryers	Al-Hassa, Qatif	1988–93	Food dryers (dates, vegetables, etc.)
Two solar-thermal dishes (50 kW)	Solar Village	1986–94	Advanced solar stirling engine
Energy management in buildings	Dammam	1988–93	Energy conservation
Solar colletors development	Solar Village	1993–97	Domestic, industrial, agricultural
Solar refrigeration	Solar Village	1999–2000	Desert application

2. Review of major RD&D projects at the ERI

2.1. The Solar Village Project

The Solar Village Project site is located near the villages of Al-Jubailah, Al-Uyaynah and Al-Higera, which are about 50 km north-west of Riyadh (altitude 650 m; latitude 24.54:47N, longitude 46.24:21E) and is representative of a typical Saudi Arabian village. The objective of this project was to use solar energy to provide power to remote villages that are not served by an electric power grid. The project was designed during the late seventies and started operation in the early eighties. The entire photovoltaic (PV) project site occupies an area of approximately 67,180 m^2. This computerized 350 kW concentrator PV electricity-generating power station includes 160 PV arrays (covering an area of 4000 m^2), with a total (direct current) peak output of 350 kW, with 1100 kWh lead-acid battery storage, 300 kVA inverter, and a solar-powered weather-data monitoring station [2]. The system is capable of completely automatic operation and is designed with both stand-alone and co-generation modes of operation.

2.2. The Solar-Powered Water Desalination Projects

One of the goals of the SOLERAS program was to incorporate solar technologies into those industrial applications that require thermal or electric energy. Under this aspect of the program, a solar-powered seawater desalination pilot plant was completed in 1984 at the coastal city of Yanbu. The plant uses an indirect-contact heat-transfer freeze process to produce 200 m^3 of potable water each day. The pilot plant also uses 18 point-focus collectors (each with a surface area of 80 m^2) with dual-axis tracking for solar energy collection. The total cost of this program was around US$35.3 million [3]. The operation, maintenance and performance (OM&P) results of the solar-powered sea water desalination plant provided gave new concepts and dimensions to the various organizations that were involved (like the Chicago Bridge and Iron Company). Those OM&P results enabled the manufacturers of collector components to use the project as a test-bed for new concepts: for example, a glass manufacturer investigated a solution to the problem of protecting mirror edges against the environment; other organizations learned more about the freeze desalination process and consequently developed new commercial equipment. This plant, however, was eventually closed down for economical and technical reasons.

In remote areas, water is essential for the life of the community, for stock life and for irrigation purposes. In Saudi Arabia, underground water is the major source, which can be brought up to the surface by using diesel engines. These engines require a continuous fuel supply to maintain regular operation, but since fuel supply to such remote areas can be very costly, solar energy is an alternative and competitive source of energy for water pumping and desalination. The first PV-powered water pumping and desalination plant was installed in 1994 at Sadus Village, approximately 70 km from Riyadh. The plant consists of two separate PV fields: one (980 Wp) is used to energize a 0.55 kW submersible pump for pumping water from a well; the other

(10.08 kWp) is used to provide power to a reverse osmosis unit (ROU), with a capacity of 24 m^3 per day, and to other accessories and equipment. Out of this PV installation, six PV arrays, each with adjustable tilt angle, are used to charge two parallel battery banks (with a total of 120 batteries). These batteries are then used to power the ROU, the ventilation fans, and other small loads. The ROU produces 600 l/h of potable water, from saline water (total dissolved solids=7000 ppm [4]). The potable water is stored in a tank, which is then used by the inhabitants of the village. Simultaneously, a separate study also sought to incorporate a solar-thermal desalination system (a pilot plant of solar stills) with the existing PV-powered ROU in order to use the high rejection rate of brine (70% of input water to ROU) for water distillation [5].

2.3. The Solar Radiation Resources and Wind Energy Assessment Projects

Reliable quantitative data on the daily and annual distribution pattern of solar energy and potential of wind energy at given locations are essential not only for assessing the economic feasibility of solar energy utilization, but also for the thermal design and environmental control of buildings and greenhouses. It has been found that the existing Saudi Solar Radiation Atlas does not cover all the parts of the country. Additionally, it does not contain the reliable information that is required for solar-energy applications, as it is based on the data collected by old and uncalibrated instruments; and the magnitude of global solar radiation has changed due to global weather variations and the environmental impacts of the Gulf War. In view of the importance of the need for exact measurements of solar radiation, the Saudi Atlas Project was initiated in 1994, as a joint R&D project between the ERI and the NREL. Twelve locations in the following cities throughout the country were carefully selected: Riyadh, Gassim, Al-Ahsa, Al-Jouf, Tabuk, Madinah, Jeddah, Qaisumah, Wadi Al Dawasir, Sharurah, Abha, and Gizan. All of these stations are connected to a central unit for data collection and all the instruments are calibrated on a regular basis (at 6 month periods) in order to derive reliable and accurate data. To promote further dissemination, the analyzed data is made available on an Internet site [6].

Similarly, data recorded in the existing wind atlas is not reliable enough for determining the wind potential. A project for wind-energy assessment was initiated by the ERI in 1995 in order to record reliable data and to assess the wind potential in Saudi Arabia. Five locations, namely, Abha, Arar, Dhahran, Solar Village and Yanbu, were selected for this purpose (namely Abha, Arar, Dhahran, Solar Village and Yanbu) as a first developmental stage of the project. The installation of monitoring and assessment equipment at those sites has been completed and data collection is still in progress [7]. The first version of the solar atlas was issued in 1999 and a wind atlas will be compiled soon.

2.4. The Solar Thermal Dish Project

The Solar Electric Stirling Engine Concentrator (the Solar Thermal Dish Project) is a joint program between KACST and the Federal Ministry of Research and Tech-

nology, BMFT, Bonn (Germany), which commenced in 1982. This program aimed to produce 50 kW of electrical power from each thermal dish. It involved the development, construction, and testing of two large-scale membrane solar concentrators, each being 7 m in diameter; and it used a large hollow reflector that tracks the sun. The units are coupled with Stirling engines to convert the collected solar thermal energy into mechanical energy that drives a 50–60 kW peak (AC) electrical generator. Both dishes were connected with the electric utility grid to evaluate the co-generation mode, and in a stand-alone mode to demonstrate the system's capabilities for providing electric power to remote sites. Results from the project revealed that development of thermal dishes with a smaller diameter would be more practical for such remote applications, because of the operational and maintenance problems and cost-effectiveness [2].

2.5. The 350 kW Solar Hydrogen Production Project

Producing hydrogen by PV methods, and storing it, is an effective way of exploiting solar energy for the subsequent use at a desirable time. The Solar Hydrogen Production Plant situated at the Solar Village, Riyadh, could have been considered as the world's first 350 kW solar-powered hydrogen-generation plant at the time of its inception. This plant uses the electricity (DC) being produced by the 350 kW photovoltaic field and the AC power from the grid supply through the rectifier. The electricity is used by advanced alkaline water electrolyze (with 0.25 m^2 of electrode area and 120 cells) to produce 463 m^3 of hydrogen per day at normal pressure. The system includes new and challenging aspects to the electrolyzer design. These new features will allow the electrolyzer to operate under variable solar conditions with an intermittent mode of operation that has not yet been investigated.

2.6. The Solar-Powered Hydrogen Utilization Project

The development of hydrogen utilization for domestic, agriculture and industrial applications (cooking, cooling, lighting, and electrical energy generation, for example) is one of the aims of the HYSOLAR program. As part of this task, a successful experiment was initiated whereby modifications to an internal combustion engine enabled it to use hydrogen as a fuel instead of petrol or gasoline.

A fuel cell is a good example of hydrogen utilization and represents an exciting power-generation technology for the coming decades. They are universally applicable due to their high efficiency (75–80%), modularity, optimum environmental characteristics, siting feasibility and for their direct utilization of natural gas as a fuel and air as an oxidant. In view of the many potential applications — for buses, trucks, remote power stations, etc. — R&D activities on PAFC were initiated at the ERI in 1991, under the framework of the HYSOLAR program.

2.7. The Solar-Powered Highway Devices Project

Modern highway safety standards require the deployment of lighting and warning devices that improve the motorist's ability to avoid potential road hazards. Due to

the difficulties in the utilization of electric power from the national grid for illuminating the highway networks, the Ministry of Communication requested that KACST conduct experiments, with the goal of determining the economic feasibility of using solar energy for highway illumination. In order to conduct this exercise, KACST has utilized the PV system to power highway devices in various remote locations within the country. The most significant projects are the lighting systems for two remote tunnels located in the southern mountains of Saudi Arabia. They generate approximately 1.5 MWh of solar-derived electrical energy each day. The total budget for these projects was US$4.5 million, and the calculated production cost of electrical energy is US$0.1 per kWh [8].

2.8. The Photovoltaic Research Project

A 3-kW PV power system has been established at the Solar Village in order to evaluate the effects of changing directional variation, rotation, dust and temperature on PV measurements, as well as to test the efficiency and output of PV systems. Performance evaluations of various PV flat-plate and concentrator module technologies are conducted on a continuous basis. A PV project, relevant to studying the effects of tracking and long-term accumulation of dust and dirt on the energy output of the PV array, was carried out. Performance results indicate an average energy gain per month of about 18% (if a single tracking atlas is used) and 20% (if dual axis tracking is used) as compared to a fixed array tilted at the site latitude. Seasonal tilt angle measurement of the passive thermohydraulic two-axis tracker at solar noon, and its comparison with the theoretical angle, revealed a discrepancy in the tracker performance. Energy loss due to dust on an array that is both fixed and tilted increased to 32% in 8 months, and was reduced to about 2% following occasional rain. Long-term dust accumulation tests on the fixed tilted array showed about a 4% loss in the energy output per month [9].

A 6-kW PV system was also installed in order to evaluate a scheme for such a system to be integrated with an electric grid, especially during peak hours, for electric load-levelling purposes [10]. Recently, a separate project on PV school lighting in rural areas has also been completed. In this project, PV lighting systems would be used for 20 schools (of the Ministry of Education) scattered throughout rural areas of the Kingdom. A number of studies have also been conducted recently by the ERI for the effective utilization of solar energy in mosques and for the protection of wildlife in Saudi Arabia [11]. These studies were conducted at the request of the relevant agencies.

2.9. Solar dryers

Drying immature dates is a problem for many countries where the relative humidity is high during the drying season. Drying dates by solar energy is important for reducing the overall maturation time, as well as for minimizing the quantity of dates lost during the process. The ERI, in cooperation with the Ministry of Agriculture and Water, conducted various research studies in order to develop the most

efficient systems for drying dates using solar energy. Within this context, a number of solar dryers have been designed, installed and experimentally tested at the Al-Hassa and Qatif Agricultural experimental sites. A new design for a solar dryer is currently under fabrication and is at the field test stage. The tested design will subsequently be handed over to those industries who are interested industry in its commercialization purposes.

2.10. The Solar Water Heating Project

It has recently been observed that the consumption of electricity has increased drastically in Saudi Arabia, which creates an imbalance between demand and supply. One way to reduce electricity consumption in water-heating sectors is to introduce solar water heating systems (SWHS) for different hot water applications (for domestic and industrial use, for example). A study on the development of SWHS at the ERI is underway, through which, a number of suitable SWHS (for different climatic areas) will be designed, fabricated (by utilizing locally available material) and field tested for all seasons. Later, the technical know-how acquired from these experimentally and seasonally tested SWHS will be handed over to interested industries for mass production and commercialization purposes. Under this scheme, a constant technical backup will be provided to the local manufacturers, enabling them to continuously upgrade and improve SWHS.

2.11. The Solar Energy Education and Training Project

Most of the developing countries fall within regions where solar energy is abundant, but it is felt that their interest regarding applications of solar energy is limited as they pay very little attention to the issue of solar-energy education (which is the basis for such a field). It is a fact that the lack of public awareness about solar energy is one of the significant obstacles that limits the utilization of an important and freely available energy source that is virtually inexhaustible. Recently, it has been reported that solar-energy educational programs should include the following points in order to facilitate effective commercialization and utilization of the technology: incorporation of solar-energy concepts into the existing curriculum at all levels, from school to university education; training programs for professionals, organizing short courses, workshops and seminars dealing with different topics of solar energy; proper campaigns to convince decision makers and industrial leaders of the need for the adaptation of solar-energy technologies; and publication of literature on solar energy technologies in non-technical language for distribution to the general public [12,13].

In order to promote the important benefits of solar energy to the general public, the ERI and the KACST participated in a number of energy related exhibitions and utilized all possible means to demonstrate the importance of solar-energy technologies. Due to the importance of solar-energy education, a survey was recently conducted by the institute on the availability of solar-energy educational programs at different educational levels around the world.

3. Performance analysis of selected R&D projects

In order to assess here the effort that has been put into the development of renewable energy sources at the rural level, the following projects are considered and evaluated.

3.1. Solar Village

Table 2 shows a summary of the 350 kW concentrator-type PV power system (PVPS). The PVPS field consists of single pedestal-mounted concentrator arrays. Each array assembly contains circular cells, and lens modules containing four Fresnel focusing lenses within in each module. The concentration ratio of each Fresnel lens is 33 suns. These lenses are made of acrylic material and glued onto molded plastic housing, which also serves as an environmental enclosure that protects the solar cells and the grooved side of the Fresnel lens. The modules are mounted on an aluminum heat sink, which provides passive cooling to the solar cells.

The operation and maintenance of a PV field (at 350 kW) for electricity supply to the Solar Village is a continuous activity of the ERI and the project has been in operation since 1981. The station supplied between 1 and 1.5 MWh of electric energy per day to three rural villages. Since its inception the PVPS has operated very satisfactorily in the dry and hot desert climate. The PV-array field generated a maximum

Table 2
PV power plant — major elements

Item	Features
PV-array field	160 concentrator arrays (12.1 m×2.7 m) with 64 parallel strings of 640 cells in series; 40,940 circular silicon (Cz) cells (5.7 cm diameter); 160 sun-tracking electronic and drive mechanisms; Fresnel lenses (quad) and plastic housing
PV-array cooling	Passive
Environment	Desert climate: 15–45°C ambient air temperature
Battery	Four lead-acid batteries (each with 120 cells in series); rated capacity of 1.6 MWh (each cell 1700 Ah)
Battery auxiliary charger	60 kW, 300 V (DC), 200 A for off-line maintenance
Inverter	300 kVA, 480 vac three-phase
Diesel generator[a]	1 MW (four 250 kW units)
Transformers	3 MVA (two 1500 kVA units); 480–13,800 vac
Switch gear	600 V (DC), 480 vac and 110 vac
Control equipment	Manual/automatic operation with HP 9845 computer
Uninterruptible power supply (UPS)	10 kVA, 110 vac inverters (two units) and a 10 kW power supply at 300 V (DC)
Instrumentation and data recording equipment	Magnetic tape, Hp 9845 computer and Hp 3052 data acquisition system
Array cleaning equipment	Purified water sprays (82°C at 100 PSI): 7.51 m (one truck mount)

[a] The diesel generators are no longer in existence and the space is being utilized for the installation of an electrolyzer for the production of hydrogen, using the power from the PV system.

power of 375 kW in 1982 but the maximum power output was reduced to 250 kW after 15 years of operation. This field generated an average monthly energy of 46,000 kWh with the field-energy efficiency ranging between 8 and 11%, and with an inverter efficiency above 90% at the initial stage of field operation. The average monthly field energy (for 3 years), as well as the invertor efficiency, are shown in Fig. 1. These profiles also show variations and degradation of the PVPS power output as compared to its initial power output. The system availability, which is the ratio of the total operating hours of the system to that of the total hours of sunshine, has changed to between 70 and 75%. Power output of the PV-array field has declined by 2.6% per year due to PV module-related failures.

Other important factors have also contributed to the degradation of the PVPS power output such as complete or partial detachment of the Fresnel lens from the housing of the half-module and the change of its colour to brown. Approximately, 3% out of the total number of half modules in the PVPS field have become brown in colour. The partial or complete detachment of the Fresnel lens will also permit dust to enter the housing, and consequently accumulation of dirt and dust on the Fresnel lenses decreases the array power output by 2.5% each month; whereas, the change from the stand-alone mode to the peak-power tracking mode of operation has increased PV-field energy generation by as much as 20%. Nevertheless, in recent times, the permanent net power of the field has been degraded by 20% due to the solder-bond delimination problem at the solar cell/ceramic substrate interface and the interconnection/ceramic substrate interface. This delimination problem has occurred as a result of the daily thermal cycling and fatigue after a long period of operation, as well as short-circuit problems, and water penetration/condensation inside the modules. The temperature of the cells was found to be excessively higher than the originally designated value, and the heat sink assembly was not sufficient to cool down the cells; but, in general, the solar energy project remains one of the

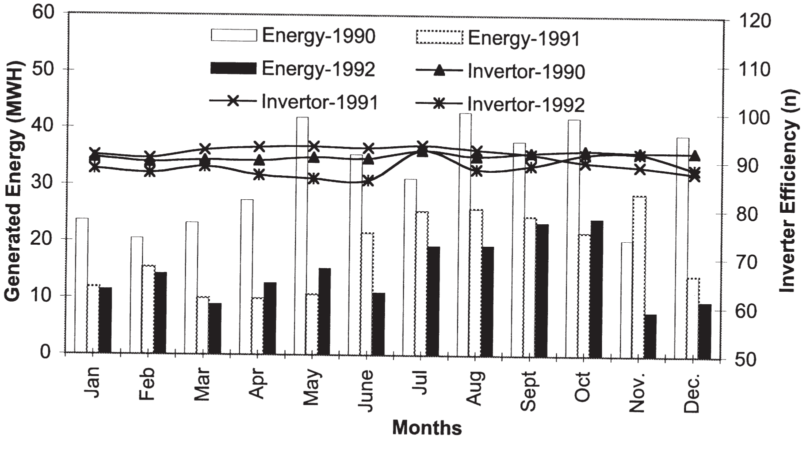


Fig. 1. Energy generated through PVPS field and related inverter efficiency in different years of operation.

most successful RD&D projects. The experience acquired through the execution of this project is rich and has proved to be significant to the understanding, maintenance and advancement of the technology. In conclusion, the following lessons have been learned:

(i) The concentrator-type photovoltaic power system is not the best option because it needs tracking systems to follow the sun. The tracking equipment necessarily makes the system sophisticated, which then requires intensive observation and maintenance. Consequently, the overall operation and maintenance costs become higher compared with the flat type.

(ii) In a dusty environment with low rainfall, such as the Solar Village, it is necessary to carry out regular cleaning of the solar panels in order to maintain the output power of the system at an acceptable level.

(iii) Large-scale PV systems are not economically viable when operated as stand-alone systems to provide energy for remote sites, due to the high cost of energy storage for use when there is no sun. However, these systems can be cost-effective if they are linked directly to the grid.

(iv) A system on this scale requires continuous monitoring and observation to avoid system failure via the failure of some minor components.

3.2. Solar water pumping and desalination

The PV-powered water pumping and desalination program is believed to be one of the most successful applications in remote areas. The ERI, in cooperation with NREL, worked jointly in a pilot project for this purpose. A team started this project from the design stage until the installation phase, then through the operation and maintenance phase. Table 3 gives a summary of the specifications of the design for PV-powered brackish water pumping and water desalination systems. The performance of the PV array in the PV-powered design is given in Table 4. The percentage deviation of measured power of the PV array, with respect to that calculated, is in the range of 19.8–24.8%; this percentage includes losses due to module mismatches, wiring, and dust [4]. It can be noted from the table that during the time of measurement the average ambient temperature was 38°C, and the PV arrays were at different operating temperatures ranging between 52 and 59°C. The measured efficiency of the PV arrays at the site varies from 7.9 to 8.5%; the measured efficiency of the inverter ranges between 90 and 96% for low and high irradiance, respectively. Initially, the average percentage recovery of ROU was variable, lying between 21 and 35%, with the recycling of a certain percentage of brine with feed water. Later, the recovery rate of the plant was enhanced to 60% after an upgrading that used different techniques. Further work is currently underway in order to increase the recovery rate.

The initial capital cost of this RD&D project was about 600,000 Saudi riyal (US$150,829), and later 140,000 Saudi riyal (US$ 37,329) was spent on its upgrad-

Table 3
PV Sadous Project

PV water pumping system	
PV array	2×7×70 Wp=980 Wp, isc=8.82 A, voc=149.8 V
Inverter	Three-phase (DC) mode — 1500 W, variable voltage and frequency (6–60 Hz) DC input: 120±20 V (DC), 12.5 A (DC)
Submersible pump installed at 50 m	Motor model MS-402, nominal power: 424–1990 W, pump model SP3A-10
PV water desalination system	
PV module	Six arrays, each with 12 series and two branches, isc=8.82 A, voc=256.8 V, total=144×70 Wp=10.8 kWp
DC system voltage	120 V (DC)
Storage batteries	2 V (with 60 in series and two parallel branches); total=120 batteries each with 1101 Ah (C-100), with recombinator
Electric charge control (ECC)	Six units with MPP, rated power=1800 W, input 0–12 A (DC), 40–25 V (DC), output 0–20 A (DC), 26–250 V (DC)
Inverter	5 kVA sinewave, 120 V (DC), 220 V (AC), 60 Hz, low and high voltage disconnect, low and high input and output current protection
Uninterruptible power supply (UPS)	250 VA, for reliable supply to the control circuit of the PV plant
Reverse osmosis unit (ROU)	600 l per hour of product water
Equipment shelter	7.6 m×3.6 m×3 m, thermally insulated walls and roof

Table 4
Performance of PV arrays in the solar-powered PV plant on 22 May 1995. Measurement time was 10:45 to 12:30. The average ambient temperature was 38°C

Array	Rated at std. conds. (Wp)[a]	Irradiance POA[b]	Array temperature (°C)	Measured (W)	Calculated at std. conds. (W)[c]	Deviation[d] (%)	Measured array efficiency[e] (%)
A-pump	980	932	52	660	827	20.1	8.5
A-1D	1680	939	54	1119	1422	21.3	8.3
A-2D	1680	936	55	1131	1410	19.7	8.5
A-3D	1680	943	56	1064	1415	24.8	7.9
A-4D	1680	951	58	1080	1417	23.8	7.9
A-5D	1680	925	59	1081	1372	21.3	8.2
A-6D	1680	915	59	1090	1360	19.8	8.3

[a] Manufacturer rating at standard conditions defined as 1000 W/m^2 at 25°C, 1.5 AM.
[b] POA: plane of array.
[c] Calculated at standard condition.
[d] Percentage of array deviation with respect to measured power; it includes losses due to mismatching between modules, wiring and dust.
[e] Module efficiency at standard conditions is 11.82%.

ing. The percentage cost of various items installed in the plant, with respect to the total cost, is 42% for PV modules and their supporting structure, 31% for batteries and electronic charge controllers, 18% for site preparation and 9% for miscellaneous equipment used on the site (the data acquisition system, the chemical dosing pump, sand filter, etc.). The O&M costs for the plant to operate at full capacity (that is 24 m^3 per day with a membrane lifetime of about 3 years) is best estimated at around 37,540 Saudi riyal (US$10,000) per year, excluding manpower. The overall performance of the ROU was satisfactory. The major problems encountered were related to membranes fouling and failure of some hardware; for example, the solenoid valve, the high-pressure pump, and the method of chemical pre-treatment of the feed water.

One can summarize the lessons learned here:

(i) In remote areas, and as it is concluded from the operation of this plant, PV systems are proven to be technically and economically feasible for water pumping and desalination.

(ii) The initial cost of this plant was high and, consequently the production cost of water increases. However, the cost can be reduced remarkably by eliminating many of the instruments and equipment that are used in this particular plant for operation monitoring, and data recording for R&D purposes.

(iii) Although the PV system is very reliable in its operation, the overall system suffers from failure of its discrete (non-PV) elements, such as membranes fouling and failure of some hardware such as the solenoid valve, the high-pressure pump, and the method of chemical pre-treatment of the feed water. Therefore, intensive monitoring is generally required in order to rectify these minor problems and to avoid any interruption of the operation of the system.

3.3. PV tunnel lighting

A PV-lighted tunnel project has been initiated as a higher priority for rural areas where electric power is neither readily nor economically available from the national grid or economically viable. Two important issues were carefully considered for lighting designs to be used in tunnels located in remote areas: one is transitional adaptation, the phenomenon that concerns the changes in visibility resulting from an abrupt change (an increase or decrease) in the prevailing luminance level of the visual field; and the other is the source of electrical energy needed to power up the lighting system. A number of stand-alone PV power systems, comprised of a PV array, battery, load and control subsystems, were installed at various locations. Valuable data about the operation and maintenance of these systems were then recorded and analyzed.

One of these projects with a capacity of 57.60 kWp has eight PV strings (sub-arrays) that were automatically connected to the DC bus during the daytime and which simultaneously power up the lamps and provide charging current to the bat-

teries. It can be seen from Fig. 2 that the system current was declining remarkably from one year to the next. By the end of its last year of operation, the lighting fixtures failed considerably so that the day load had almost equalled the night load. The PV project showed satisfactory operation during its earlier stages; however, a significant degradation of the system output was experienced. The main reason for this degradation was the high failure rate of the lighting fixtures as well as damage to the batteries. This failure could be due to one or more of the following factors: the design of the system, the type or specifications of particular elements, and also the nature of the maintenance activities. Unfortunately, the failure problems were not corrected at the appropriate time, which subsequently led to accumulated failures of the system components, and consequently a complete failure of the system. The performance of the other tunnel lighting projects was essentially similar so that the projects were eventually terminated.

One can again summarize the important lessons learned:

(i) Special care is necessary during the design stage of any PV system, particularly for issues regarding the physical size of the system. Proper selection of the system elements is also important and it must be done according to specific standards.
(ii) Tunnel lighting systems in Saudi Arabia were believed to be a successful application. However, in practice, they ultimately failed due to a lack of the proper experience on the part of the O&M contractors.
(iii) Education and training programs for local firms on how to operate and maintain PV systems are essential. Otherwise, the O&M costs will be very high if they are to be provided by the system's suppliers or the R&D centers.

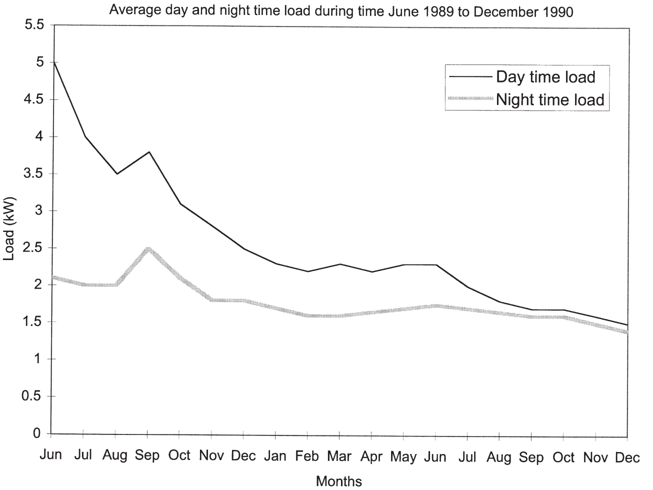


Fig. 2. Average day and night time load from June 1989 to December 1990.

3.4. Solar water heaters

The average solar heating energy, produced per square meter of collection area is about 30 kWh per day. The calculated cost of 1 kWh of useful heating energy from solar power is around 0.13 Saudi riyal (US$0.035). Recently, a special metallic absorber for flat plate collectors has been designed, with a hydraulic press for bulk manufacturing. The design of the tested absorber, and other technical know-how, will be handed over to interested industries for commercialization purposes. It is reported, that a thermosyphon domestic SWHS (based on locally fabricated solar collectors with an area of 3.6 m^2) could provide sufficient hot water for a family of five persons living in Saudi Arabia and it would cost 4500 Saudi riyal (US$1200.00). This shows that the final cost of locally fabricated and environmentally tested SWHS will be about 60% cheaper than imported SWHS [14]. Obviously, costs will be drastically reduced via mass production. It is noteworthy to mention that in the year 1984, KACST introduced imported units of forced closed-type solar water heating systems for domestic water heating purposes. More than 1100 solar flat-plate collectors have been installed on the rooftops of 373 residences of different categories (like villas, terraced houses, and apartments) in the KACST campus at Riyadh. Each family residence is equipped with three solar flat-plate collectors (with a total surface area of 6.36 m^2) and a hot water storage tank with a capacity of 65 gallons. The total effective surface area of the solar flat-plate collector at the KACST campus is 2249 m^2, which generates about 67 MWh of useful heating energy each day. These systems are still functioning but with some problems in the controllers, and a study is underway in order to fully evaluate these systems.

3.5. Fuel cells

After successful completion of the R&D activities on the PAFC technology (that is, acquiring 'in-house' know-how for developing half-cells, mono-cells, and 100- and 250-W stacks), a 1 kW PAFC stack was also demonstrated at the ERI. Valuable experience — such as acid management techniques, control of hydrogen gas leakage and intermixing of hydrogen and air in the cells of the stack (due to lack of electrolyte in the matrix and so on) — led to an improved design and fabrication of the 1 kW PAFC stack. These lessons are useful for scaling-up the power-generating modules (to 10–50 kW) for power utility applications in remote areas of Saudi Arabia [15]. Initial steps have been taken to initiate PEMFC R&D activities at ERI, since this technology has several potential advantages and applications over the PAFC technology (such as power density, high efficiency and low operational temperature). In another project, locally available internal combustion engines, and ceramic mantle gas lamps, have been modified in order to use hydrogen as a fuel for small-scale demonstration purposes. A commercial thermoelectric power generator, originally designed to be fuelled by methane or propane, has been modified to operate using hydrogen. Safe and reliable utilization of hydrogen has therefore been demonstrated. Most of the required components used in these activities were designed and fabricated locally by ERI scientists, therefore, the staff of the ERI have also gained professional experience in this field.

4. Concluding remarks

Despite the fact that Saudi Arabia is a leading oil producer, its continuing commitment to RD&D on the utilization of solar energy is based on the long-term importance of renewable energy sources as in playing a supportive role to conventional sources. Oil (one of the exhaustible sources) ought to be more wisely used in developing other products that are more beneficial and useful to mankind. Saudi Arabia also benefits from the R&D efforts on renewable energy sources in the following ways:

(i) Qualifying manpower at local research centers: the joint work of local people with expertise scientists from developed countries is a good opportunity for them to gain experience. The ERI, Saudi universities and local industry have gained qualified experts in the field of renewable energy research, development and applications.
(ii) Establishing laboratories for supporting R&D in the field of renewable energy at the main research centers in the KACST and at universities.
(iii) Helping to transfer the technology of the PV industry to Saudi Arabia: a number of local factories are importing ready made solar cells and then assembling PV modules to meet the demand of the local market. Even though these industries have been in operation for the last 10 years, the PV market potential in Saudi Arabia is still quite small.

The installed PV system in Saudi Arabia is about 4 MWp (accumulated capacity). The main obstacle is the high cost of energy produced by PV but this is generally a worldwide problem. Therefore, a lot of effort is required in the development of PV systems with the ultimate goal of reducing costs to a level that is economically viable and comparable with conventional energy systems.

Similarly, the field applications of solar-thermal energy in Saudi Arabia requires further study. Nevertheless, it has been proved that the manufacturing of solar water heaters is much cheaper in Saudi Arabia and its utilization is economically viable. However, much more attention needs to be paid to the production of hot water for potentially large users of solar energy such as hotels, hospitals and industry. Solar-thermal assemblies can be easily incorporated into such facilities as multi-stage flash desalination, and the possibilities of using solar absorption cooling systems could be explored. Parabolic troughs, evacuated tubes, and heat-pipe solar collectors should also be designed and tested in the field in Saudi Arabia. At a later date, this design and the manufacturing know-how can be transferred to interested industries and should be utilized for future RD&D projects.

The solar-energy RD&D activities throughout Saudi Arabia have confirmed that it has a multitude of practical uses. These include lighting, cooling, water heating, crop/fruit drying, water desalination, the operation of irrigation pumps, the operation of meteorological stations, and in providing road and tunnel lighting, traffic lights, road instruction signals, and for small applications at remote sites. However, effective

utilization of solar energy in Saudi Arabia has not yet made reasonable progress mainly due to several obstacles, some of which are listed as follows:

(i) The wide availability of oil, its superiority to solar energy as a source of energy and its relatively low cost.
(ii) The dust effect, which in some parts can reduce solar energy by 10–20%.
(iii) The availability of governmental subsidies for oil and electricity generation and non-availability of similar subsidies for solar energy programs. Such subsidies inhibit the chances for solar energy to compete with the commercial energy sources that are available. If such subsidies must continue then solar energy will require incentive programs.

Researchers in the field of solar energy have responsibilities beyond the scientific and technical aspects of research and beyond the efforts made for publication of their findings. These include dissemination and utilization of scientific knowledge gained in laboratories, and interaction with potential users, policy makers, planners, and manufacturers.

The ERI has made progress in its attempts to promote the use of solar energy with several experimental developments of solar technologies carried out through actual field studies at remote sites, far from the comfort of laboratories, where such systems are actually serving remote communities. This has been rewarding, because it offers researchers the chance to interact with the actual users and provides a better environment for testing systems under real-life conditions. All such R&D projects should be continued with greater emphasis placed on its commercialization. To this end the following steps could be adopted for the effective process of dissemination and commercialization of solar-energy technologies:

(i) Promote interaction between research centers and local industries for mass production of experimentally and seasonally tested solar-energy technologies and devices.
(ii) A major expansion of R&D efforts, field testing, and demonstration of solar-energy projects with the purpose of increasing the awareness about utilization of renewable energy.
(iii) Promotion of solar energy education and training programs and the creation of a local credit system, and other facilities that enable the general public to access, own and operate solar-energy technologies.

Overall, the experience gained in the field of renewable energy R&D during the last two decades has been very valuable. The international joint programs have assisted in the establishment of a series of independent RD&D projects on solar energy by the ERI, and several other users throughout the country. Henceforth, its further utilization and dissemination to the general public would serve to increase job opportunities and improve the standard of living in remote areas, and would also

boost industrialized development through the transfer of the field-tested technology to local industry. Again, education and training programs on solar energy, the creation of local credit and other facilities enable encourage the public to gain access to solar-energy technologies.

The importance of using renewable energy in Saudi Arabia will not only be confined to meeting the demands of remote sites, but can also contribute to the national grid, helping to meet the peak-load demand during the summer months (especially after recent restructuring of the electricity sector). As a result of the new electricity tariff, it is expected that PV demand will gradually increase in the coming years, and will consequently have a greater role to play in energy management and conservation; especially since the government is starting to considering new measures for energy conservation, with special attention being given to remote regions.

As a result of Saudi Arabia's efforts in R&D of renewable energy sources, valuable lessons have been learned, which are believed to be very useful to other countries with similar climatic conditions, as well as to the scientific community in general. The overall lessons gained are listed as follows:

(i) In the developing countries, it is not worth spending funds on basic research for developing renewable energy sources. Instead, such efforts should be directed to finding applications of those systems that have already been developed in industrialized nations.
(ii) Researchers in the field of renewable energy have responsibilities beyond the scientific and technical aspects of research and beyond the efforts made for publication of their findings. These include dissemination and utilization of scientific knowledge gained in laboratories, and interaction with potential users, policy makers, planners, and manufacturers.
(iii) Seawater desalination by solar energy is still not cost-effective when compared with convention energy sources (gas and oil), as implemented in Saudi Arabia.
(iv) Assessment projects on renewable energy resources have helped Saudi staff gain valuable experience, especially in the fields of instrumentation, calibration, data collection, and monitoring and analysis.
(v) The solar-thermal dish project revealed that development of thermal dishes with a smaller diameter would be more practical for remote applications because the operational and maintenance problems of large-scale dishes are complex and they are not cost-effective.
(vi) Hydrogen production by PV systems can be used to store solar energy in a convenient form that can subsequently be used at a time of need; for example, power generation and domestic applications.
(vii) The need to regularly clean the PV array in dusty weather in order to maintain an acceptable level of system output.
(viii) PV systems have proven cost-effective in Saudi Arabia in supplying the peak demand of the electricity grid, as well as in supplying energy for small loads at remote sites.
(ix) Close contacts and effective interaction need to be maintained between centers of R&D and local industry in order to bring the new developed product to practice.

(x) There is a need to promote proper education and technical training on renewable energy applications within academia, as well as a need to increase public awareness about the benefits of utilizing these sources of energy.

Acknowledgements

The author expresses his deep thanks and appreciation to the KACST for permission to publish the results of R&D projects on renewable energy which they have funded. Thanks is also due to the staff of the ERI who participated directly or indirectly in this work.

References

[1] Report on Saudi Arabia's energy and economic statistics, as well as an up-to-date analysis of its oil and gas industry. United States Energy Information Administration, January 2000 [report available on Internet, May 2000: http://www.eia.doe.gov/emeu/cabs/saudfull.html].
[2] Huraib FS, Hasnain SM, Alawaji S. Lessons learned from solar energy projects in Saudi Arabia. In: Proceedings of the World Renewable Energy Congress IV, June 15–21; CO, USA, 1996.
[3] Thompson C. Summary of administration and management of SOLERAS. MRI/SOLERAS 30001, October 1987.
[4] Alawaji S, Smiai M. Performance and development of PV-plant for water pumping and desalination for remote areas in Saudi Arabia. In: Proceedings of the World Renewable Energy Congress IV; CO, USA, 1996:441–6.
[5] Hasnain SM, Alajalan S. Coupling of PV-powered RO brackish water desalination plant with solar stills. Desalination — The International Journal on the Science and Technology of Desalting and Water Purification 1998;116(1):57–64 [also presented at the Sixth Arab International Solar Energy Conference (AISEC-6), 1998 March 29–April 1; Muscat, Oman, and earned the Best Paper Award certificate).
[6] Renewable Resource Data Center. Data available on the Internet: http://rredc.nrel.gov/solar/new_data/Saudi_Arabia, May 2000.
[7] Alawaji SH. Wind energy resource assessment in Saudi Arabia — 1: Network design and description. Renewable Energy 1996;7(4):319–28.
[8] Alawaji SH, Eugenio N. Tunnel lighting — a remote area application for photovoltaic power system. Washington, DC: ASES, 1993.
[9] Smiai MS, Alawaji S. Performance of variously tilted PV modules in the Riyadh area. In: Proceedings of the 12th European Photovoltaic Solar Energy Conference, vol. 2, 1994:1938–41.
[10] Smiai MS, Alajlan SA, Huriab FS, Alsalim SH, Eugino MN, Bagazi S. PV-grid connected system. Project research report. Riyadh, Saudi Arabia: Energy Research Institute, KACST, January, 1998.
[11] Hasnain SM, Smiai SM, Alajlan S. Solar hot water and stand-alone PV systems for a mosque in the Riyadh region — Saudi Arabia. AJSE 1999;24(2B):187.
[12] Hasnain SM, Elani UA, Alawaji SH, Abaoud HA, Smiai MS. Prospects and proposals for solar energy education programs. Appl Energy 1995;52:307–14.
[13] Hasnain SM, Alawaji SH, Elani UA. Solar energy education — a viable pathway for sustainable development. Renewable Energy — Int J 1998;14(4):387–92.
[14] Hasnain SM. Development of solar water heating systems at KACST. Proposed research project report. Riyadh, Saudi Arabia: Energy Research Institute, KACST, December 1994.
[15] Ghouse M, Abaoud H, Al-Boeiz A. Operational experience of a 1 kW PAFC stack. Appl Energy 2000;65:303–14.